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Signature of Rhine Valley sturzstrom dam failures in Holocene sediments of Lake Constance, Germany

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Abstract

Landslide-dammed lakes that form upstream of large-scale rockslide-avalanches (=sturzstroms) present an enormous potential hazard to downstream areas. Such failures are recorded in the Early Holocene sediments of Upper Lake Constance (Germany) by the presence of two clastic layers that were emplaced around 9400 cal. YBP. The sedimentology of these layers contrasts sharply with the typical Late Glacial and Holocene lacustrine sediments present beneath the floor of the lake. Sedimentary structures and the magnetic fabric of these clastic deposits strongly suggest that they were emplaced by hyperpycnal underflows related to catastrophic floods that entered the lake from the Rhine River. From stratigraphic and geologic data, it is inferred that the hyperpycnite deposits are directly related to the failure of two sturzstrom dams and the draining of the dammed lakes that developed upstream from them. These lakes were dammed by the Flims and the Tamins sturzstrom deposits, respectively. Sedimentologic data from Lake Constance indicate that the two successive events occurred within a very short time interval, probably not exceeding several years. Consequently, these lacustrine deposits provide essential information about the morphogenic evolution of the Rhine River valley during the Early Holocene and about the sturzstrom events that occurred during the same time interval.

Keywords: Rockslide-debris avalanche; Lake sediments; Flims; Tamins; Hyperpycnal flow

1. Introduction

Large-scale rockslide avalanches (=sturzstroms) are gravity slides that transform into rapid granular flows (>100 m s^{-1}) that affect the flanks of mountains and volcanoes of high relief (Hungr et al., 2001). The resulting deposits can dam valleys and disturb the

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normal flow of rivers. Consequently, sturzstrom-dammed lakes develop upstream (Gaziev, 1984; Costa and Schuster, 1988). Landslide-dammed lake failures constitute a major hazard to downstream areas (Eisbacher and Clague, 1984; Cruden, 1985; Butler et al., 1986; Schuster and Costa, 1986; Costa and Schuster, 1988; Trauth and Strecker, 1999; Bookhagen et al., 2001; Capart et al., 2001; Lefèvre and Schneider, 2003; Ermini and Casagli, 2003). Numerous historical examples are known (Hadley, 1978; Kojan and Hutchinson, 1978; Voight, 1978; Schuster and Costa, 1986; Costa and Schuster, 1988; Reneau and Dethier, 1996; Davies and Scott, 1997; Zhou et al., 2001). From the analysis of these historic cases, it appears that sturzstrom dammed-lakes are relatively ephemeral. For instance, in the case of the Mayunmarca rockslide, Peru, in 1974, the dam was breached 44 days after the landslide emplacement, releasing a flood with a peak discharge of about 10^4 m^3 s^{-1} (Kojan and Hutchinson, 1978). Statistical analysis by Costa and Schuster (1988) indicates that about 85% of sturzstrom dams fail during the first year after the event. But some lakes can last for hundreds or thousands of years, depending on factors such as size and volume of the dam, the cohesion of the dam material, and the rate of inflow to the impoundment (Costa and Schuster, 1988).

Along the Rhine River valley in Grisons, Switzerland, two major Holocene sturzstrom deposits were recognized in the Flims and Tamins areas (Abele, 1997; Schneider et al., 1999 and references therein)

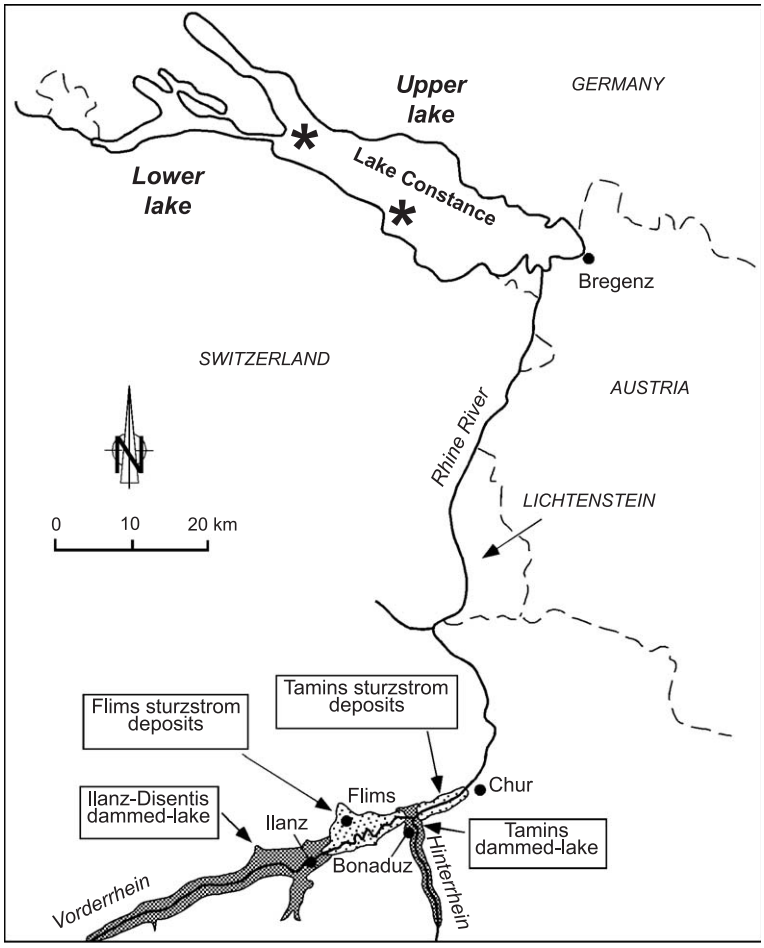

Fig. 1. Location map of the deposits of Flims and Tamins sturzstroms, and of Lake Constance. Asterisks represent the location of cores retrieved from Lake Constance. The locations of landslide-dammed lakes developed upstream from the sturzstrom deposits are also represented.

near the city of Chur (Fig. 1). Field studies indicate that major lakes developed upstream of the Flims and Tamins sturzstrom dams. About 100 km downstream, Lake Constance (called the Bodensee in Germany) constitutes a deep basin into which the Rhine River flows. Consequently, the sediments in this lake have recorded events related to failure of the sturzstrom dams. The purpose of the present work is to describe clastic deposits that are interstratified within the sedimentary record of Lake Constance (Germany) that are very likely related to failure of the Flims and Tamins landslide dams. The presence of these clastic layers suggests that large-scale dam breakages occurred. Herein, we discuss a possible scenario for these events using data from both the sturzstrom deposits and from sedimentary cores retrieved from Lake Constance.

2. Geologic setting

2.1. Sturzstroms in the Rhine River watershed

Two voluminous sturzstrom deposits occur in the Rhine River valley (Switzerland) south of Lake Constance in Flims and Tamins sturzstroms.

The Flims sturzstrom (Fig. 1) was a major morphogenic event in the valley, mobilizing 12 km^3 of Jurassic calcareous rock material of the Calanda massif that was emplaced in the Vorderrhein valley (Schneider et al., 1999; Pollet and Schneider, 2004, and references therein). This event occurred in Early Holocene time, around 8400 YBP, based on a ^{14}C age that has been determined from woods fragments collected from the base of the distal sturzstrom deposit in the Rabiusa valley (von Poschinger and Haas, 1997). Another wood sample from the same place was dated at the Centre de Datation par le Radiocarbone, University Claude Bernard, Lyon 1 (analysis Lyon-1273 OxA), gave an age of 8360±85 YBP. The corresponding calibrated age according to the Early Holocene calibration curve of Stuiver and Reimer (1993) is 9487 cal. YBP. The Flims sturzstrom therefore occurred a short time after the withdrawal of the glacier that carved the Vorderrhein valley, which had occupied the valley throughout late Pleistocene time.

The deposits dammed the Vorderrhein valley to a minimum height of more than 400 m above the valley floor. The dam impounded a volume of water estimated to be around 20 km^3, which extended 30 km upstream, to an area between the modern cities of Ilanz and Disentis (Schmitter-Voirin, 2000; Wassmer et al., in press). According to the present-day topographic surface of the Flims sturzstrom deposit, the maximum elevation of the dam-lake surface is estimated to be around 1100 m a.s.l. Evidence of the former lake includes fluvial-lacustrine gravel and clay deposits in the area of Ilanz–Sagogn, as well as deltaic deposits near Laax (left side of the Vorderrhein valley) and Glenner (right side; Abele, 1970). Detailed morphologic observations and the character of the upper facies of the sturzstrom deposits strongly suggest that overtopping of the dam occurred by way of three separate flow paths (Fig. 2). Water overtopped the dam after filling all accessible topographic depressions on its surface. At the onset of overtopping, low-cohesion debris (upper granular facies) at the top of the sturzstrom was rapidly incised, resulting in gully formation. These gullies are characterized by the presence of isolated washed sturzstrom blocks and by a washed facies (matrix-poor sturzstrom debris) at the top of the deposits. One of these gullies ultimately became dominant, developing into the future Vorderrhein river gorge (Ruin'Aulta). During the rapid draining of the dammed lake, strong erosion of the sturzstrom deposits led to the formation of a wide U-shaped valley within the gorge (Fig. 3.1), which is clearly evident 1 km downstream of the railway station of Versam-Safien (Chli Isla; Fig. 3.2). At present, the gorge's profile is V-shaped, the result of normal fluvial erosion since the breach (Fig. 3.1).

The *Tamins sturzstrom* deposits occur in the Rhine River valley, 2 km downstream of the confluence of Vorderrhein and Hinterrhein in Reichenau that coincides with the most distal deposits of the Flims sturzstrom (Figs. 1 and 2). The estimated volume of the deposits is around 1.3 km^3. The sturzstrom traveled a total distance of 13.5 km from the Säsagit massif to the floor of the valley (Scheller, 1971; Shaller, 1991). The age of the Tamins event is poorly constrained. The transported rock material consists mainly of Mesozoic deposits of the Calanda massif. The deposits consist of large masses of landslide debris that occupy the floor of the Rhine River valley. The most spectacular morphological characteristic of the deposits is the presence of conical hills up to 68-m high above the present Rhine River valley floor

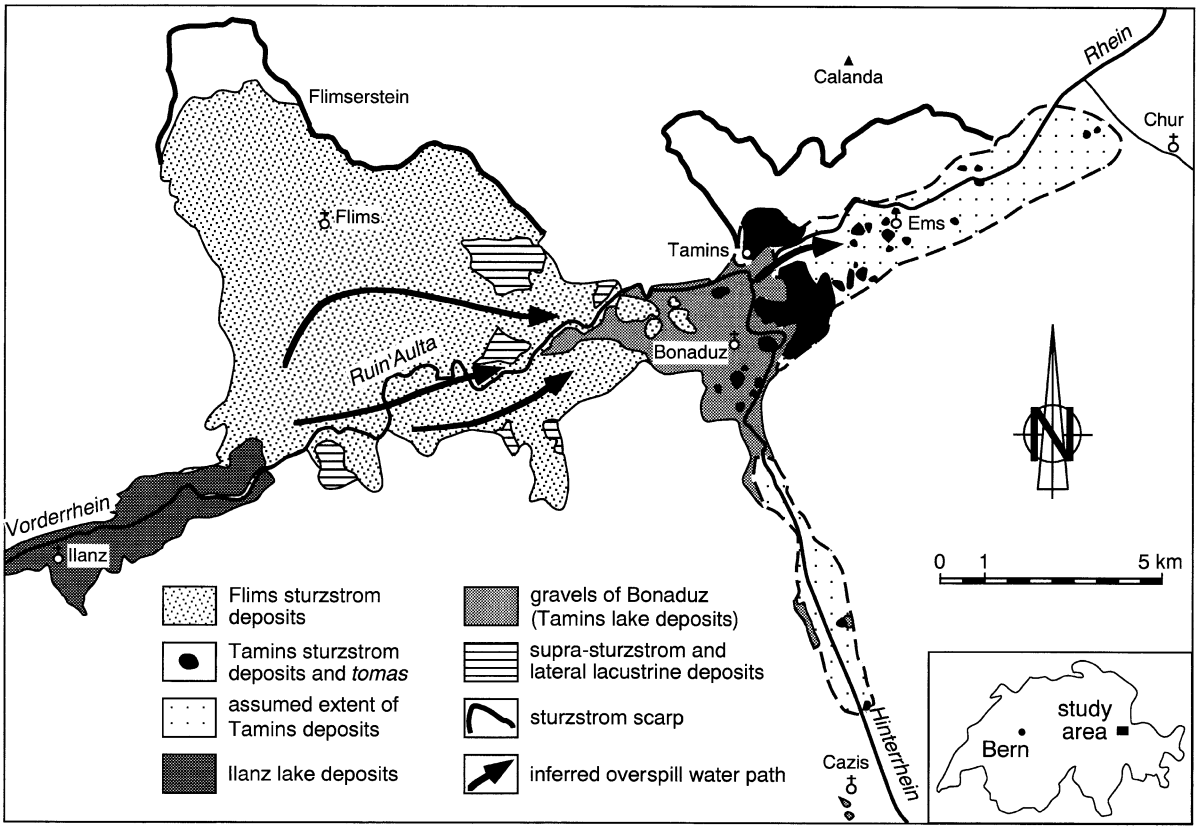

Fig. 2. Sketch map of the deposits of the Flims and Tamins sturzstroms and their related fluvial-lacustrine deposits.

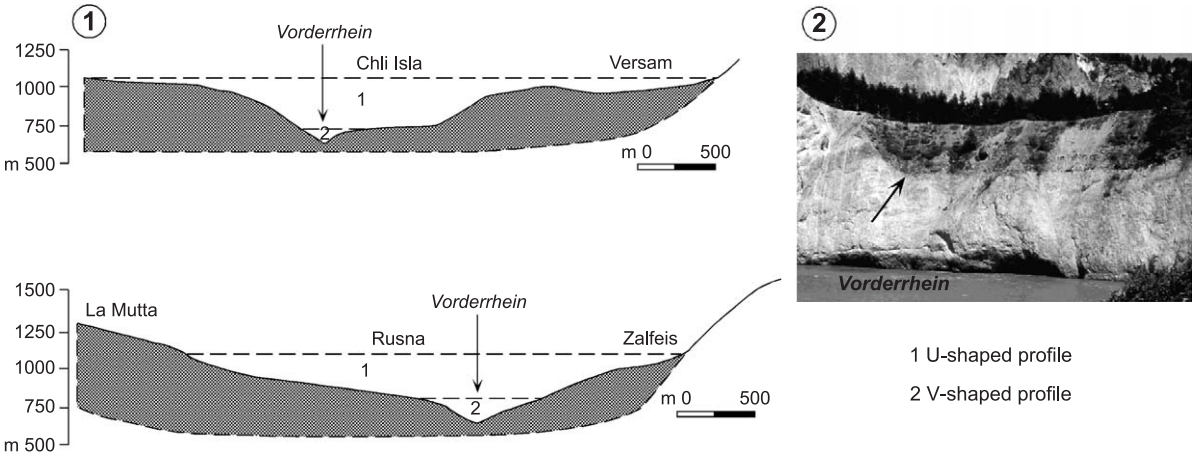

Fig. 3. (1) Topographic profiles of the Rhine River gorge (Ruin'Aulta). Note the change of the profile from U-shaped to V-shaped from top to base. (2) Photograph of the U-shaped profile of the paleo-Vorderrhein valley floor (arrow) at Chli Isla.

around the villages of Tamins, Ems, Felsberg, and the western suburbs of the city of Chur. These buttes are called, in the rhetic-romanche toponymy, *tomas* (from the latin *tumulus* that means hill). Some blocks moved upstream in the Hinterrhein valley as far as the village of Rodels, a distance of about 10 km. The *tomas* are composed mainly of Mesozoic Calanda limestone with very minor orthogneiss. The slopes of most of the *tomas* are draped with thin, discontinuous layers of gravel (Rougier, 1980).

The Tamins sturzstrom deposits dammed the Rhine River valley downstream of the confluence between the Hinterrhein and Vorderrhein. This led to the deposition of a thick sequence of fluvial deposits upstream in the area of Bonaduz and Rhäzüns villages, as far as the village of Cazis (Fig. 2). Following Abele (1997), we refer to these deposits as the Bonaduz gravels. These gravels were deposited after emplacement of the Flims sturzstrom because some distal blocks related to the former event near Bonaduz (at the mouth of the Ruin'Aulta gorge) are covered by deltaic sediments associated with the lake impounded by the Tamins sturzstrom. The elevation of the dam is difficult to establish but very likely reached 700 m a.s.l. Consequently, the dammed lake reached at least the present location of the city of Thusis in the Hinterrhein valley. Geophysical investigations indicate that the Quaternary lake deposits that occupy the Rhine River valley in the area of Bonaduz are more than 300 m deep below the present river floor (Pavoni, 1968 and references therein). Projection of the slide plane of the Tamins sturzstrom beneath the present-day valley floor suggests that the dam may have reached more than 200 m in thickness. Pavoni (1968) suggested some interactions between the Tamins sturzstrom and gravelly masses during emplacement. However, the Bonaduz gravels were deposited upstream of the sturzstrom deposit and attest to the development of a dammed lake. Their thickness is at least of 50 m. The nature of the gravels suggests that both the Vorderrhein and Hinterrhein were sources of the deposits. Indeed, in the Bonaduz area, fluvial deposits contain granite fragments that originated from the Vorderrhein valley. These were deposited in a deltaic system at the mouth of the Vorderrhein downstream of the Flims sturzstrom deposit. The presence of gravels from the Permo–Triassic Verrucano Formation in the area of Rhäzüns indicates that the deltaic deposits were simultaneously fed from the Hinterrhein. The Bonaduz gravels also form terraces along the flanks of the Hinterrhein valley as far as the village of Cazis (Abele, 1970; Fig. 2).

2.2. Sedimentary deposits in Lake Constance

Lake Constance (Fig. 4.1) is located in the molasse basin of the northern Alpine foreland at the border between Germany, Switzerland, and Austria. The lake, which is the second largest lake in Europe and Europe's largest reservoir for drinking water, is of glacial origin. It is classically divided into two subbasins (Kiefer, 1972; Braun and Schärpf, 1994): the deeper and larger Upper Lake to the South–East and the shallower Lower Lake, located west of the city of Constance, where the Rhine River flows out of the lake. The Upper Lake covers an area of 534.7 km^2 and contains about 48.5 km^3 of fresh water. The central region of the Upper Lake corresponds to a deep longitudinal depression with a flat bottom (Fig. 4.1), the maximal depth of which reaches 254 m. Lake Constance is a typical hard-water lake where calcite precipitates in spring or summer when phytoplankton blooms increase alkalinity. The Rhine River constitutes the main inflow (draining the Alps over an area greater than 6100 km^2) and provides up to 90% of the annual allochthonous clastic influx into the lake (Müller, 1971).

Numerous high-resolution 3.5 kHz and air gun seismic reflection surveys have been performed in both the Lower Lake and the central region of the Upper Lake Constance (Müller and Gees, 1970; Schröder et al., 1998; Wessels, 1998a). These surveys reveal the presence of three superposed acoustic facies within the sedimentary infill of Lake Constance. From bottom to top, these facies are defined as:

1. a sequence of distal turbidites which lie on strongly deformed and slumped sediments deposited in the very early deglaciation period;
2. a stratified sedimentary fill which occupies subbasins in the Lower Lake;
3. upper postglacial sediments.

Sediment thicknesses inferred from the acoustic data decrease from south to north, reflecting maximal postglacial clastic accumulation in the area of the Rhine River delta.

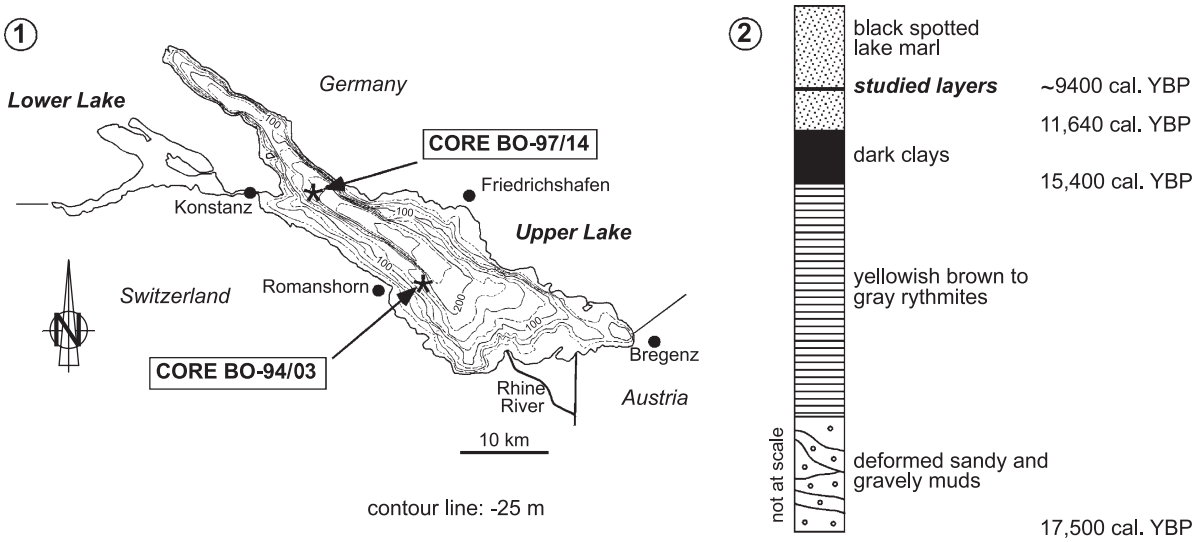

Fig. 4. (1) Simplified bathymetric map of Lake Constance with location of the studied cores. (2) Synthetic lithostratigraphy of the sedimentary column of Lake Constance (from the data of the southern slope; Wessels 1998a).

Data from sedimentary cores indicate that turbiditic clastic sediments dominate the sedimentary sequence in the southern and central parts of the lake. A large delta developed in the alpine Rhine Valley. Five generations of channels are present in the foreslope of the delta, reflecting several natural shifts of the river mouth (Schröder and Niessen, 1988; Schröder et al., 1998). These channels are the main sources of underflows to the deep central basin.

The style of sedimentation varied with time in the Upper Lake (Fig. 4.2; Wessels, 1998a,b). The Late-Glacial development of Lake Constance (17,500–11,640 cal. YBP) records various types of sedimentation. Sediments deposited early in the deglaciation consist of alternating strongly deformed beds of massive, clayey silt to sand. These deposits are overlain by yellowish brown to gray lacustrine rhythmites (17,500–14,500 cal. YBP) which record an important wind-blown loess influx into the lake. A reduction in the eolian influx and total sedimentation rate occurred during deposition of the yellow rhythmites between 15,400 and 11,640 cal. YBP, reflecting the effects of postglacial warming. At the same time, an increase in productivity led to an increase in total nitrogen content and the occurrence of iron sulfide in the sediments.

During the Holocene period (< 11,640 cal. YBP), the Rhine River began to flow directly into the southeastern end of the lake. This major hydrologic change occurred around 7000–9000 cal. YBP, following the complete sedimentary infilling of lakes upstream in the upper Rhine River valley (Keller, 1994). This change resulted in a decrease in authigenic calcite and a correlative rise in allochthonous calcite deposition in lake sediments. Since 7000–8000 cal. YBP, the Rhine River has been the major source of sediments in Lake Constance, reflected as a coarsening of the clastic influx to the lake. Since this time, sedimentation has been dominated by massive brownish gray to dark gray mud deposits, with black-spotted (iron-sulfide concretions) lake marl at the top of the sequence. Along the northern slope of Upper Lake Constance, these deposits grade into light brown to dark gray laminated silts deposited primarily by sediment-laden interflows (Wessels, 1995).

3. Data collection

Two piston cores were obtained in Lake Constance sediments (cores BO94/03 and BO97/14 [BO indicates "Bodensee"]) during coring campaigns conducted in 1994 and 1997 aboard the working ship *Bär* (Wessels, 1998a). Core BO94/03 was obtained on the western flank of the main central basin of Upper

Lake Constance at a depth of 160 m. Core BO97/14 was retrieved 12 km to the northwest at a depth of 180 m. The cores were split longitudinally; visual observations were conducted on the working half-sections of cores. Thin sections were made for specific regions of interest. A Malvern laser-diffraction microgranulometer at the University of Lille was used to evaluate the <2-mm fraction to determine high-resolution grain-size characteristics and better understand the evolution of the deposits. A 5-mm sampling interval was used in the two key clastic layers and in the black-spotted lake marl layers bracketing them. Grain-size parameters (mean grain size, sorting, and skewness) were calculated using the criteria of Folk (1968). Thin sections were obtained from the two clastic layers as well as the intermediate deposit. The bulk mineral compositions of the different facies were examined by means of X-ray diffraction (XRD) at the University of Lille.

Measurements of magnetic susceptibility anisotropy (AMS) can be used to obtain information regarding the depositional environment of the sediments (Taira, 1989; Tarling and Hrouda, 1993). AMS visualizes the volumetric fabric of the deposits. We collected oriented 1 cm^3 samples by pushing nonmagnetic plastic square boxes into the surface of both black-spotted lake marl and clastic layers of core BO 97/14-05. Measurements of the AMS were performed using a Kappabridge KLY-2 device at University of Lille (Laboratoire de Sédimentologie et Géodynamique). Each sample was analyzed in 15 directions to determine the magnitude and directions of the maximum, intermediate, and minimum AMS axes. The geometry of the AMS ellipsoid (Hrouda, 1982; Tarling and Hrouda, 1993) can be established by means of its main magnetic susceptibility axes: $K_{max}=K_1$, $K_{int}=K_2$, and $K_{min}=K_3$, respectively. K_{max} is generally parallel to mean long axis of the constituent particles and therefore to the transport direction. To evaluate the relationship between depositional processes and magnetic fabrics, the AMS parameters were calculated for each sample using the following equations (Hrouda, 1982; Borradaile, 1988; Jelinek, 1981):

1. the magnetic lineation: $L=K_1/K_2$
2. the magnetic foliation: $F=K_2/K_3$
3. the shape parameter (Jelinek, 1981): $T=(2\eta_2-\eta_1-\eta_3)/(\eta_1-\eta_3)$
4. the degree of anisotropy (Jelinek, 1981):

$$P_j=\exp\sqrt{\langle 2[(\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2]\rangle}$$

5. the alignment (Ellwood, 1975): $F_S=K_1^2/\sqrt{K_2^2K_3^2}$

where $\eta_1=\ln K_1$, $\eta_2=\ln K_2$, $\eta_3=\ln K_3$, and $\eta_m=\sqrt[3]{\eta_1\eta_2\eta_3}$.

The magnetic fabric is coaxial to the sediment fabric (Rochette et al., 1992; Tarling and Hrouda, 1993) and is characterized by the magnetic foliation (oblate, $K_{max}\sim K_{int}>K_{min}$, and $-1>T>0$) and magnetic lineation (prolate, $K_{max}>K_{int}\sim K_{min}$, and $0>T>1$). The shape parameter T allows the identification of the type of magnetic fabric, which is related to conditions in the sedimentary environment. The degree of anisotropy P_j quantifies the relative strength of the magnetic fabrics (Hrouda, 1982). The alignment parameter F_S is related to the magnitude of K_{max} and represents the development of a linear fabric (Ellwood, 1975). In subaqueous sediments, the orientation of magnetic grains depends on the intensity of the bottom currents; F_S increases with the energy of the bottom currents (deMenocal, 1986; Park et al., 2000). The characteristics of the magnetic fabric can be visualized by use of binary diagrams, in which F, L, T, P_j, and F_S are plotted.

4. Observations and results

4.1. Description of the clastic layers

Within cores BO94/03 (Section 03) and BO97/14 (Section 05), two closely spaced clastic layers composed of brownish gray, clayey silt are interstratified within the Holocene black-spotted marl (Fig. 5). They differ completely from all other deposits ever cored in the lake and appear to be related to exceptional events as compared with regular sedimentation in Lake Constance. We call the lower layer L1 and the upper one L2. These layers are separated by a narrow 1- to 1.5-mm-thick whitish silty interval in both cores. The two layers differ in thickness in the two cores. L1 and L2 were exclusively recognized in these two localities; they are not present in other cores (total combined length of 85 m) recovered from Lake Constance since 1988.

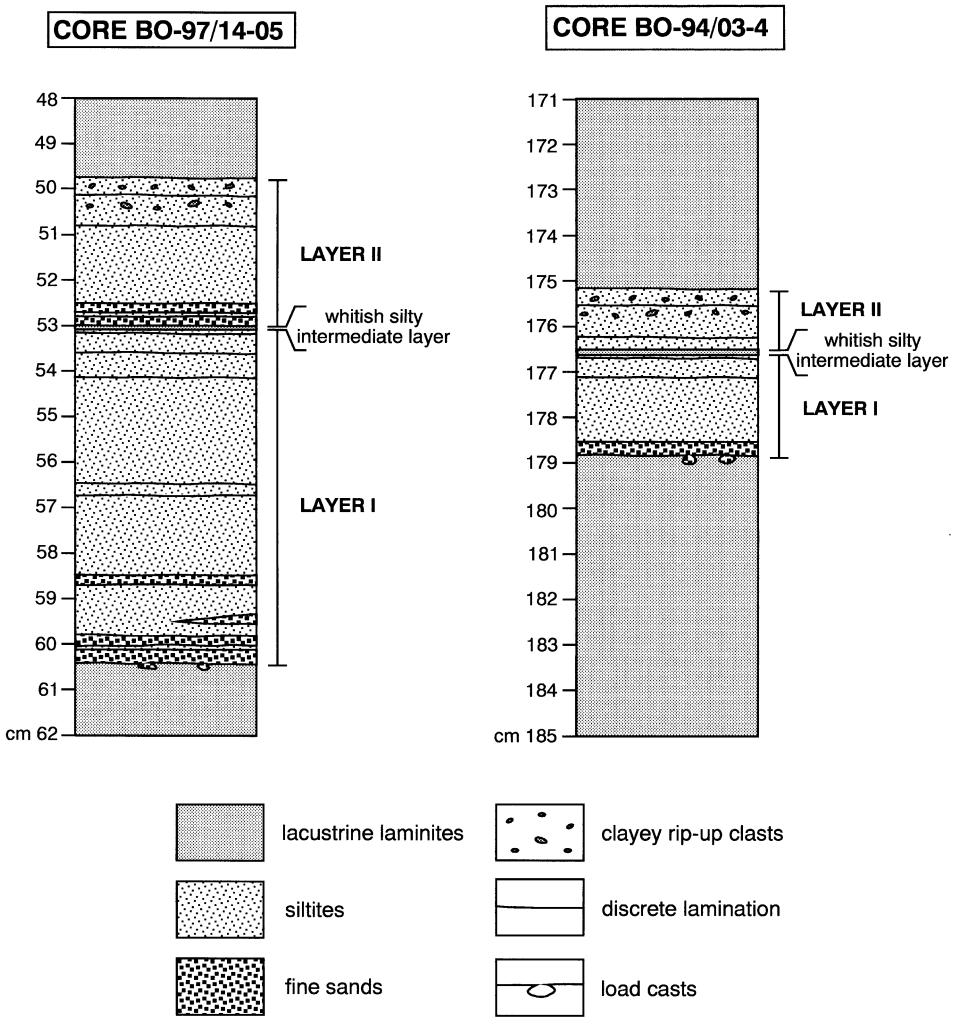

Fig. 5. Detailed sedimentologic logs of L1 and L2 in cores BO97/14-05 and BO94/03-04.

Layer 1 is 7.5 cm thick in core BO97/14-05 and 2.0 cm thick in core BO94/03-05 (Fig. 6). In both cores, L1 is normally graded with a sharp basal contact that exhibits small load casts. Four ~ 2-mm-thick fine sand laminae are present near the base of Layer 1 in core BO97/14-05. These laminae represent a marked contrast with the enclosing massive silty deposits. The thickness of the second and third laminae from base is somewhat variable laterally. Near the base, the silts are planar laminated. Towards the top, the brownish silt grades upward and shows a discrete planar lamination. X-ray imaging confirms the presence of this discrete lamination. In core BO94/03-04, the silt grades upward and discrete planar lamination is present at the top.

Layer 2 is thinner than L1. It is 3.5 cm thick with black oxidation specks in core BO97/14-05 and 1.4 cm thick in core BO94/03-05 (Fig. 6). Two basal sandy laminae are present in core BO97/14-05. In core BO94/03-05, only a single laminae and color layering related to various concentrations of oxidized iron sulfides are visible in L2.

The tops of both L1 and L2 are characterized by the presence of rounded and elongated clayey rip-up clasts that parallel the general planar lamination. These rip-up clasts average 0.2 mm in length. Their

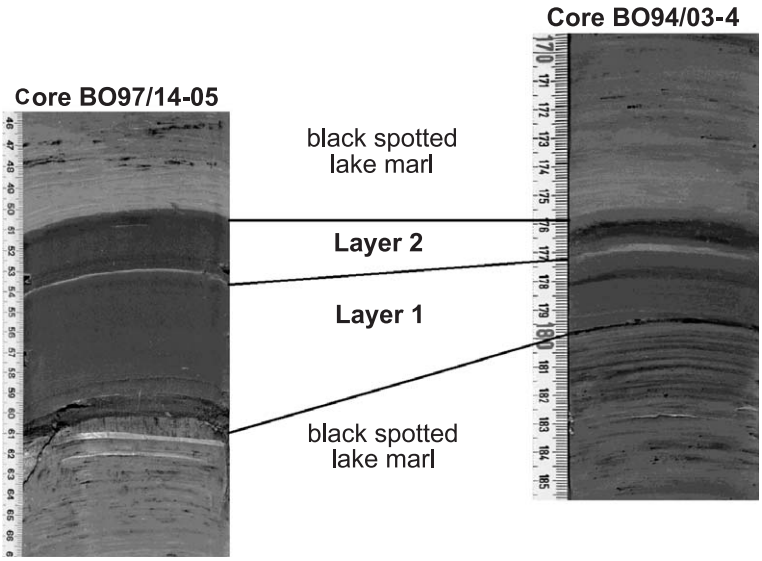

Fig. 6. Photographs of the sedimentary sequences in cores BO97/14-05 and BO94/03-04.

presence on the top of L1 attests to some erosion of the lake sediments before the emplacement of L2.

4.2. Intermediate silty layer

A whitish intermediate silty layer is present between L1 and L2 in both cores (0.4–0.7 mm thick in core BO97/14-05 and 1 mm thick in core BO94/03-05). Thin section analysis of this interval in core BO97/14-05 reveals that it is composed of an alternation of six dark and lighter laminae. The uppermost is contorted and discontinuous as result of emplacement of L2.

The period of time represented by the intermediate layer is very short. If the laminae are biannual (i.e., a light/dark couplet deposited annually), then the sedimentary interval between L1 and L2 could have been deposited within a time span of 3 years. Two blooms per year leading to calcite precipitation are possible in such settings however so that the six laminae could conceivably represent a time interval as short as 1.5 years. The thickness of the intermediate interval is 1 mm in core BO94/03-05. Wessels (1998a) has estimated a sedimentation rate for the time period 8000–10,000 cal. YBP (*cf.* discussion below) of ~ 30 cm/1000 years. This rate is consistent with deposition of the intermediate layer over a period of ~ 3 years. Three years is a minimum age because erosion of the top of this silty interval cannot be excluded during emplacement of L2. As the thickness of the intermediate silty layer is similar in both cores, it suggests that the time interval between emplacement of L1 and L2 is in the range of a few years.

4.3. Grain-size analysis

Data from core BO97/14-05 (Fig. 7) indicate that the sandy horizons contain a high proportion of silt and clay, which constitute a matrix for the sandy particles. The sand content varies from 1.4% to 13.8% in L1 and from 1% to 4% in L2. The mean grain size varies from 10 to 35 μm in the clastic layers and strongly contrasts with the mean grain size (2 μm) in the enclosing black-spotted marl. The granulometer results confirm the normal grading of L1 and L2. The base of L1 displays variations in both grain size and sorting because of the presence of the sandy laminae. The mean grain size is strongly correlated to variations in sorting and negatively correlated to the skewness. These characteristics suggest variations of the flow energy, at least during L1 emplacement. In core BO94/03-04, sediments of the two clastic layers are generally finer than in core BO97/14-05 but display a similar vertical variation in grain-size parameters.

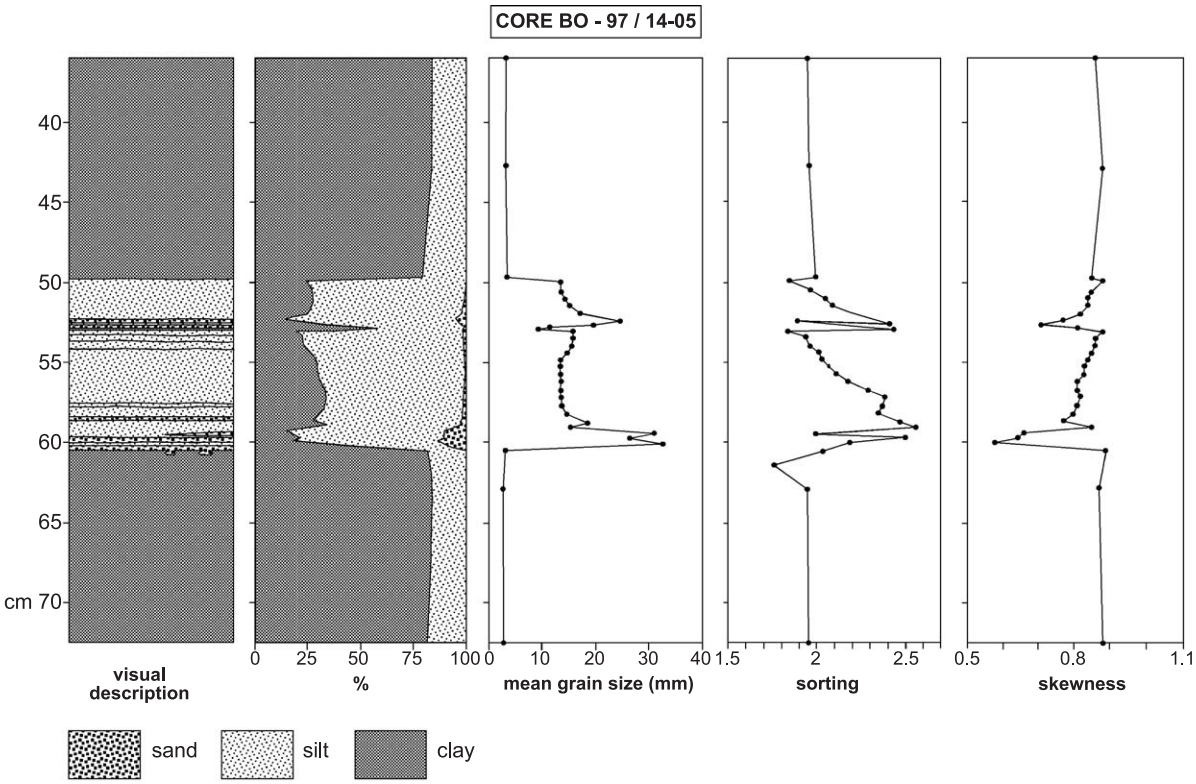

Fig. 7. High-resolution grain-size analysis of L1 and L2 in core BO97/14-05 (0.5-cm sampling interval).

4.4. X-ray diffractometry

X-ray diffractograms obtained from the black-spotted lake marl and from L1 and L2 display variations in the mineral content of the sediments. Black-spotted lake marl consists mainly of calcite with minor dolomite, chlorite, quartz, and feldspar. L1 and L2 contain a higher proportion of allochthonous quartz and feldspar, and also illite. L1 and L2 are enriched in illite and chlorite at the base. This mineralogy is very typical for sediments of Lake Constance, suggesting an influence of clastic influx from the Rhine River watershed, which constituted the main source of clastic material for Lake Constance during the Holocene.

4.5. Anisotropy of the magnetic susceptibility

The mean volumetric magnetic susceptibility is weak ($<130\times10^{-6}$ SI units) in both clastic layers and enclosing black-spotted lake marl (Table 1). This finding suggests that the magnetic grains are primarily paramagnetic (clay minerals, i.e., chlorite and illite) and diamagnetic (quartz, calcite, feldspar).

Table 1
ASM parameters of core samples (Lake Constance)

Sample	Core depth (cm)	K	L	F	T	P_j	F_S
A	36.0	25.33	1014	1025	0.282	1048	1054
B	42.8	30.63	1004	1029	0.739	1048	1037
C	48.0	29.38	1004	1028	0.774	1046	1036
D	50.0	101.06	1009	1118	0.857	1191	1137
E	52.0	107.97	1012	1119	0.812	1196	1145
F	54.0	71.93	1008	1110	0.858	1179	1128
G	54.5	87.18	1004	1121	0.928	1192	1130
H	57.5	92.45	1004	1111	0.924	1176	1120
I	59.5	127.02	1005	1101	0.897	1162	1113
J	62.0	32.06	1003	1033	0.840	1053	1039
K	63.0	42.82	1006	1028	0.643	1047	1040
L	72.7	33.53	1006	1034	0.675	1057	1047

K: mean bulk volume susceptibility in S.I. units $\times10^{-6}$; L: magnetic lineation; F: magnetic foliation; T: shape parameter; P_j: anisotropy degree; F_S: alignment (see text for explanations).

The magnetic susceptibility is however almost three times higher in L1 and L2 ($85-130 \times 10^{-6}$ SI units) than in the lake marl ($25-45 \times 10^{-6}$ SI units). The vertical variation of the mean volumetric magnetic susceptibility (Fig. 8.1) is closely correlated with the mean grain size as the result of concentration of clastic material. Because chlorite and illite are enriched at base of L1 and L2, the mean volumetric magnetic susceptibility increases from top to base. Sample F (Table 1) displays a relatively high mean volumetric magnetic susceptibility because it contains the intermediate whitish silty layer and both top of L1 and base of L2. Consequently, the mean susceptibility is a result of the influence of all three components.

In general, the magnetic fabrics of the deposits are relatively weak. It is highly improbable that the magnetic fabric changes were caused by coring disturbances, both because of the inclination of K_{min}, which is between 72° and 85°, and because the fabric is normal to the bedding plane in all samples. It is also unlikely to be influenced by bioturbation, which is absent in the deposits. Vertical changes in the orientation of the three axes of anisotropy reveal interesting contrasts between the black-spotted marl deposits and the L1 and L2 beds (Fig. 9). The magnetic anisotropy is very weak in the black-spotted lake marl. Within L1 and L2, by contrast, K_{max} and K_{int} increase strongly and display very similar values, whereas K_{min} decreases. The magnetic fabric corresponds to oblate AMS ellipsoids. This character is confirmed in L1 and L2 where the fabric appears more foliated than within lake marl (Fig. 8.3). Because the magnetic foliation

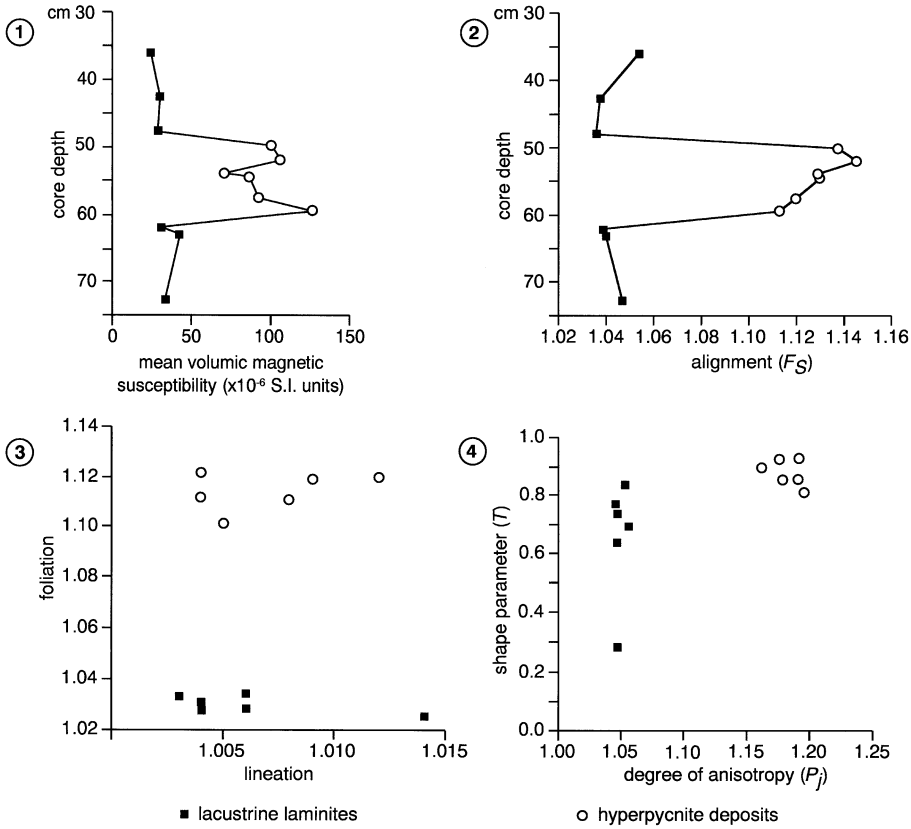

Fig. 8. AMS data of the studied interval in core BO97/14-05. (1) Vertical evolution of mean volumetric magnetic susceptibility versus core depth. (2) Vertical variation of the alignment parameter (F_S) with core depth. (3) Lineation versus foliation. (4) Degree of anisotropy (P_j) versus shape parameter (T).

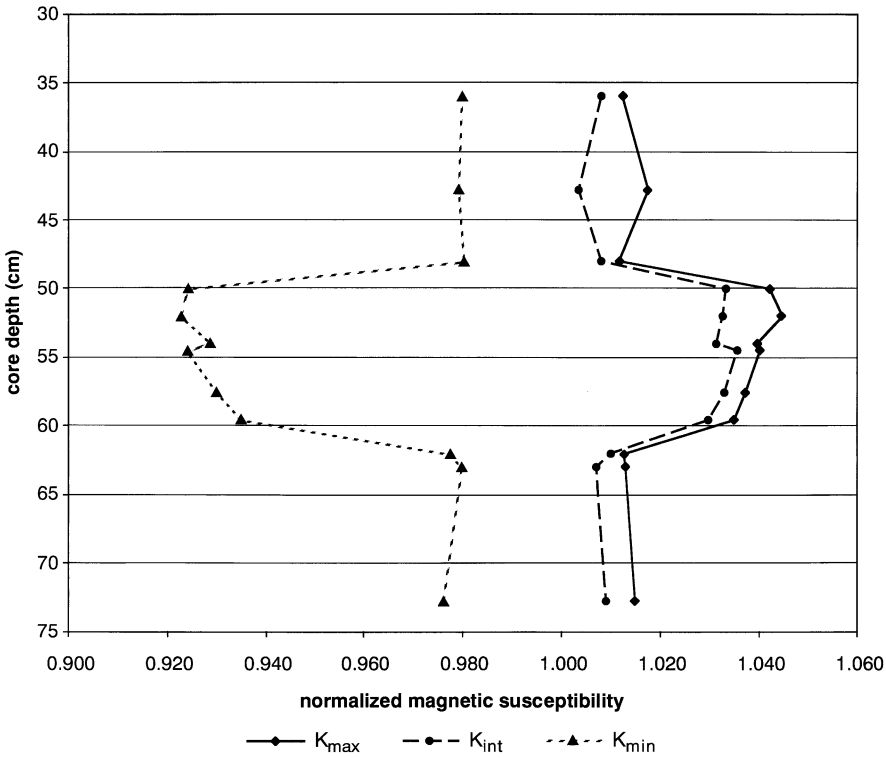

Fig. 9. Vertical variation of the magnetic anisotropy axes with core depth. Values of the magnetic susceptibilities are normalized.

is stronger in L1 and L2 than in the marl, the fabric must be the result of depositional processes and not postdepositional compaction. The magnetic lineation is similar for both lake marl and clastic layers L1 and L2. In the lake marl, the shape parameter T is variable but positive (Fig. 8.4). The degree of anisotropy P_j is also very weak (<1.05). These data indicate a magnetic foliation of the lake marl. The magnetic fabric is better resolved within L1 and L2 with T around 0.9, and P_j up to 1.14. Moreover, the alignment parameter (F_S) of the deposits varies with core depth (Fig. 8.2). It is abruptly higher within L1 and L2, progressively increasing up to 1.145 in L1, and coinciding with the higher values of P_j. By contrast, F_S does not exceed 1.06 within the lake marl. These data strongly suggest that sedimentary processes active during deposition of lake marl contrasted sharply with those active during deposition of layers L1 and L2.

5. Discussion

5.1. Emplacement mechanisms and significance of L1 and L2 deposits

The sedimentary characteristics of L1 and L2 deposits indicate that they were emplaced by gravity flows, completely different from the sedimentation of the enclosing black-spotted marl. The origin of L1 and L2 by gravity flows is supported by the general grain-size characteristics of the deposits, as well as by the AMS and X-ray diffractometry data. Gravitational settling of the particles is the predominant sedimentation mode for the lake marl as suggested by the weak magnetic foliation. The magnetic fabric of L1 and L2 deposits is characterized by a more significant foliation but also by a higher degree of anisotropy. Moreover, the positive correlation between P_j and F_S argues in favor of control by a current parallel to the lake floor. Variations of F_S within L1 deposit suggest

changes in the flow velocity during sedimentation. This characteristic is also supported by similar evolution of the skewness grain-size parameter.

L1 and L2 were deposited from gravity flows that display variation in intensity during the sedimentation. L1 and L2 appear similar to characteristic T_d and T_e subunits of the turbiditic Bouma sequence (Bouma, 1962). However, grain-size data do not completely support this similarity. Although the sediments generally exhibit normal grading, the increase in mean grain size above the basal contact of L1 in core BO97/14-05 indicates an increase in flow energy that transported the sediments before final emplacement of the deposits. This characteristic is consistent with the AMS data.

All the data suggest that the clastic layers were deposited from hyperpycnal currents acting along the floor of Upper Lake Constance. Such currents are related to floods in rivers that enter lakes or the sea (Sturm and Matter, 1978; Mulder and Syvitsky, 1995). Hyperpycnal currents in Lake Constance are related to variations of the discharge of the Rhine River into the lake. Major floods of the Rhine River therefore controlled deposition of L1 and L2, both of which correspond to hyperpycnite deposits. This origin is also supported by the mineral content of L1 and L2, which clearly indicates an allochthonous clastic source. As L1 and L2 were recovered within two cores located at 12 km from each other, these layers appear to reflect relatively voluminous clastic deposition events in Lake Constance. These major floods exhibited significant variations in flow rate, as indicated by grain-size variations within the depositional sequences and magnetic fabric.

Because of their sedimentary characteristics, L1 and L2 cannot be related to potential seiche events in Lake Constance because oscillatory processes lead to the emplacement of homogenites that do not display strong vertical grain-size variation, except at their base (Chapron et al., 1999 and references therein). Moreover, the L1 and L2 deposits are much thicker than other turbidites identified in the lake, ruling out local sedimentation as an origin of the layers.

L1 and L2 deposits were recovered only at depths exceeding 160 m. This fact very likely reflects the energy of the floods. Most of the clastic material was deposited in the deltaic environment at the mouth of the Rhine River. The turbid bursts induced by the floods were energetic enough to reach the distal deep basin of Upper Lake Constance (where L1 and L2 were recovered in core BO97/14-05) but were too energetic to allow particles fall out from the suspension in more proximal areas of the lake during the flood peaks. L1 and L2 deposits are thicker in core BO97/14-05 than in core BO94/03-04. The latter is located in a more proximal, shallower location (160 m.b.l.l.). The thickness differences are the results of channeling of the hyperpycnal flow by the deep basin, and L1 and L2 in BO94/03-04 represent lateral or levee deposits that were formed from the flow cloud enriched in finer particles by elutriation processes. The flow in the area of core BO94/03 was certainly less energetic than in the area of core BO97/14. The small thickness (~ 1 mm) of the whitish intermediate silty layer however indicates a very short time interval (several years at most) between the two successive flood events.

5.2. Age of L1 and L2 deposits

L1 and L2 were emplaced from sediment gravity flows that exerted some erosive effect on the lake floor as attested by the presence of clayey rip-up clasts at the top of layer L1 and L2. These limited erosional processes are also confirmed by the perturbations that affect the laminae at the top of the whitish silty layer intercalated between L1 and L2. This thin, laminated (probably varved) interval argues for a short-time interval between emplacement of L1 and L2. Absolute dating of flood-derived deposits is always problematic because of the mixing of organic matter of different provenances, in this case, from both the Rhine River valley and Lake Constance. No individual wood fragments were found. An age of 9400 cal. YBP has been obtained for the L1–L2 interval from high-resolution correlation of cores 88/47 and 94/03 by means of carbonate content (Wessels, 1998a). The age of the Flims sturzstrom is nearly identical—9487 cal. YBP. Consequently, the sturzstrom and the flood events were nearly coincident in time.

5.3. Dam failure chronology

As L1 and L2 emplacements were related to major floods of the Rhine River during the early Holocene, it is necessary to envision two major, closely spaced events in the watershed that could be responsible for

these floods. The only reasonable possibility is the failure of the sturzstrom dams, releasing impounded water from the Flims and Tamins areas (Figs. 1 and 2). The organization of the sturzstrom and fluvial-lacustrine deposits in this area allow us to propose the following chronology:

(1) The Flims sturzstrom was emplaced first and dammed the Vorderrhein valley around 9487 cal. YBP (Fig. 10). The Flims sturzstrom predated the Tamins sturzstrom, as indicated by the presence of large Flims sturzstrom blocks in the Bonaduz area (composed in part of Graubünden lustrous shale that is absent in the Tamins sturzstrom deposits) that are surrounded with and partly covered by Bonaduz gravel. Emplacement of the Flims sturzstrom resulted in the formation of the Ilanz–Disentis lake upstream of the blockage, with a lake level at about 1100 m a.s.l. This lake lasted for a relatively short period, perhaps several years to several tens of years.

(2) The Ilanz–Disentis lake drained by progressive but rapid failure of the Flims sturzstrom dam. Failure resulted from overtopping of the dam, as attested to by the presence of gullies with washed sturzstrom material at top of the dam and by the shapes of the present-day profile of the Vorderrhein gorge (Fig. 3). Rapid draining of the lake resulted in a large-scale flood in the Rhine River valley downstream. When this flood reached Lake Constance, it induced the generation of the first hyperpycnal underflow, forming sedimentary unit L1. It is possible that a large part of the transported clastic material of the flood was transported by a debris flow close to the source and was trapped in the former lakes located in the Landquart and Sargans areas (Fig. 10). The clastic

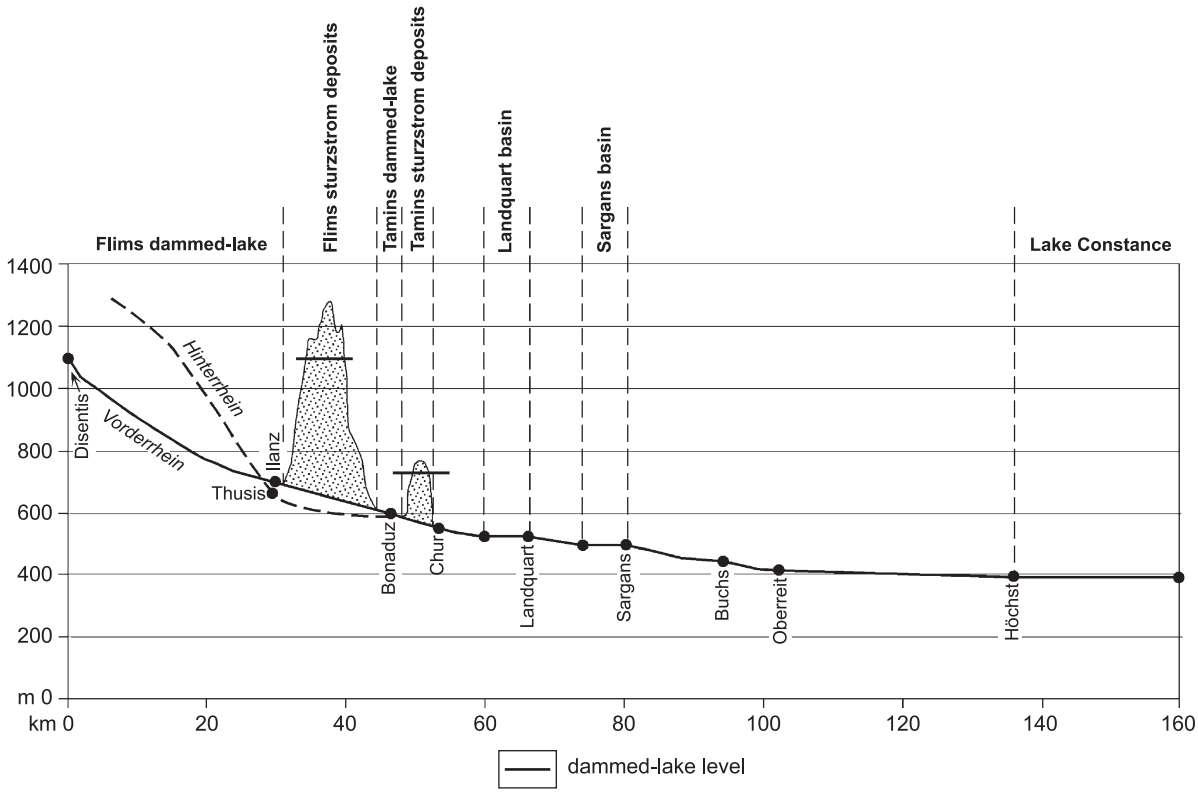

Fig. 10. Topographic profiles across the floors of Vorderrhein, Hinterrhein, and Rhine River valleys, showing the locations of the Flims and Tamins sturzstroms dams. Horizontal lines on dams represent the inferred maximum lake levels.

influx from the Rhine River into Lake Constance became more efficient when these basins filled in around 6000–8000 YBP (Keller, 1994), an event that led to a decrease in the supply of authigenic calcite to the lake (Wessels, 1998a).

(3) The Tamins sturzstrom very likely occurred shortly after draining of the Ilanz–Disentis lake, again damming the Rhine River valley (Fig. 10), this time just downstream of the confluence between Vorderrhein and Hinterrhein. The Tamins lake developed upstream from the sturzstrom dam in the Hinterrhein valley. It was fed by clastics from both the Hinterrhein and Vorderrhein rivers. As the general slope of the Hinterrhein valley is steeper than that of the Vorderrhein valley and as the Tamins sturzstrom dam reached only about 700 m a.s.l., the lake which formed upstream from the Tamins sturzstrom was much less voluminous than the earlier Ilanz–Disentis lake.

(4) The Tamins dammed lake failed a short time after emplacement of the sturzstrom (months to years). The dam failure resulted in a second major flood, of lesser volume than the first. The presence of gravelly superficial deposits on flanks of the *tomas* (Rougier, 1980) provides evidence of the passage of the flood following the dam failure. Because the Landquart and Sargans basins were already filled by clastic material at this time (likely filled during the first major flood event), the second flood easily reached Lake Constance and fed the second hyperpycnal flow.

6. Concluding remarks

The relative timing of the Flims and Tamins sturzstroms remained problematic until recently. The presence of two superimposed hyperpycnite layers at the base of the Holocene sedimentary column in the deep basin of Upper Lake Constance testifies to the occurrence of two closely spaced major floods in the Rhine valley. Because L1 and L2 were likely deposited within a very short time span (several years), we favor a hypothesis in which two successive, closely timed sturzstrom events occurred in the Rhine River valley shortly after deglaciation. Both sturzstroms resulted in the formation of landslide-dammed lakes. The Flims sturzstrom occurred first, impounding a lake that drained catastrophically soon thereafter. A similar sequence of events followed a short time later in response to emplacement of the Tamins sturzstrom. From all the data and analyses presented in the current report, it appears crucial to pursue additional field studies in the Tamins area to clarify the precise timing of these catastrophic events. The presence of the two hyperpycnite layers in the sedimentary record of Lake Constance attests to the magnitude of the floods related to the two dam failures. These characteristics are in general agreement with historical data compiled by Costa and Schuster (1988) regarding landslide dam lake formation and failures. Consequently, these lacustrine sedimentary signatures allow us to better refine the chronology of major mass-wasting events in the Rhine River valley.

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